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# The dynamical regime of Active Regions via the concept of persistent homology

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**Abstract**

Solar activity is a space-time complex of events that are produced by Sun magnetic fields. One of the results of this activity are solar flares. The solar flares occurs mainly in the areas with especially strong magnetic fields called Active Regions (AR). Observation phenomenology indicates that significant change in the magnetic field topology precedes strong flares. Now high frequency temporal sequences of AR magnetograms containing flares are available from the space observatory Solar Dynamics Observatory (SDO). We analyzed them to investigate changes in complexity by using methods of computational topology. As possible descriptors of flares we used topological invariants: the Euler characteristics and Betti numbers. These characteristics of course do not pretend to be the comprehensive description of topological complexity but they are simple in construction and intuitively clear. We found that the large variation of the Betti numbers and Euler characteristics are preceded or accompanied by a large flares. These results give us hope that approach based on computational topology could be useful in the task of monitoring magnetic field evolution and should be developed in future


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*Keywords:* Solar Flares, persistent homology, computational topology;

## 1. Introduction

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Large solar flares are the most dramatic result of the evolution of magnetic fields in sunspots. Energetic flares which occurred near the center of the Solar disc could make the disastrous damage on the terrestrial and space equipment. Large flares tend to occur in the big groups of spots, so called Active Regions (AR) of the Sun. These groups may contain more than a dozen of spots with different polarities forming topological complex spatial configuration of the magnetic field.

The problem of early prediction of a high-energy releases period, which is accompanied by big flares is an important task of solar flares. At this moment numerous approaches has been published. Roughly they could be divided in two classes, see Manolis and Georgoulis [1]. First is based on fundamental physical parameters and second is based on proxy attributes or phenomenological properties of Solar data. The list of commonly used and accepted parameters could be found in article Barnes and Leka [2]. Each parameter has its' own context and physical meaning. In the majority of investigations, these parameters were applied to big statistical samples of flaring and non-flaring regions. Barnes and Leka [2] have analyzed and compared existing approaches to solar flares prediction using the photospheric magnetic field and concluded that there are no significant differences between all of them and despite of the high statistical success rate none of them could be used for robust daily flare forecast. As a conclusion authors advise as one of the further approaches to consider the evolution of magnetic field. Such approach is very demanding to the quality of data. It should be constant-quality, high-cadence and long time series of photospheric magnetograms. Such data at first was available from the SOHO observatory and now it is available through improved successor Helioseismic and Magnetic Imager, see in Hoeksima et al. [3]of the Solar Dynamics Observatory. NOAA AR 11158 was the first large flare product AR tracked by the SDO laboratory.

The processes leading to flare appearance and energy release are still not fully understood, see Barnes and Leka [2]. The initial impulse phase of the flare as generally believed is driven by magnetic reconnection, which leads to changes in topology of magnetic fields. So-called new emerging magnetic flux appears before the solar flare. The reasons to believe that new emergence flux connected with the solar activity are discussed in our previous work Knyazeva et al. [4]. In practice, it should be seen in additional critical points appearance, or emergence of thin structure in the "old" magnetic field. In other words, it should be seen in changes of topological complexity of magnetic field, but for analysis we need to introduce a formal criteria of complexity. Our approach is mainly based on the ideas of random fields topological complexity description from the book of Adler [5].

## 2. Topology of Solar Magnetogram

Magnetograms used for numerical analysis of Solar magnetic field could be seen as an image of Sun disc where each pixel represents a strength of magnetic field. Some magnetographs can measure only line of sight (LOS) from the observer component of magnetic field; others could measure also a transverse component from which all three components of magnetic field are deduced. The first magnetograph, which produced continuous, constant-quality, high-cadence and long time series of magnetograms, was MDI (Michelsondoppler imager) at the space observatory SOHO. It could measure only LOS component. It successor HMI (Helioseismic and Magnetic Imager) could also measure a transverse component. A spatial resolution of MDI data is ~ 2"/pixel or 1500 km, with 1024x1024 for full solar disc, time cadence is 96 min.SDO data has resolution of ~0.5" pixel and time cadence at 12 min. Up to now we have only worked with the line of sight component, because it is obtainable from both instruments. But, of course additional component will also be analyzed in future. We work with a fragment of Solar disc containing an AR. We use automated system of Active region patches which track the location throughout life time developed by SDO observer's team, full description in Hoeksima et al. [3].

To describe a topological complexity of magnetic field we suggest using methods of computational topology. Let's consider an excursion set of the random field:

$$A_u = \left\{ \mathbf{x} \in \Omega \middle| B(\mathbf{x}) \geq u \right\}$$

Where $\Omega$ is a compact region formed by the pixels $\mathbf{x} \in \Omega, \mathbf{x} = (x_1, x_2)$, and the magnetic field $B(\mathbf{x})$ exceeds a specified level $u$ .Recall the ideas of "Morse filtration" of excursion sets from Adler [5]. Obviously that for two excursion sets $A_u \subseteq A_v$ if $u \geq v$ .Going from one level set to another components of excursion set may merge and new components arise. Also the topology of these components may change, holes could appear and disappeared. For classification structures of objects formalism of algebraic topology is used, precisely persistent homology. In two-dimensional space $X$ the zeros homology $H_0(X)$ is generated by connected components of $X$, the homology $H_1(X)$ generated by the holes; the numbers of the components and the holes called $\beta_0$ and $\beta_1$ respectively, see in Edelsbrunner [6]. Then the difference between Betti numbers will be the Euler characteristics:

$$\chi = \beta_0 - \beta_1 \qquad (1)$$

If we will track the changes in the homology of the sets as the function of levels sets and fix the moments of creating and destroying homologies we receive persistent homology. The term persistence comes from that fact that changes in homology arise only at critical points of the fields. Between them homology stay "persist". The broad description of basis of homology could be found in Edelsbrunner [6]. It is useful to describe persistence homology via notion of barcodes. A bar could be constructed for each homology group, in our case components and holes. The bar starts with the birth of component and ends with the level of component. First point will be the level of birth the second level of death. It is useful to draw it on the plane using the beginning and the end of the barcode as point coordinates. As the result we obtain a set of points, which lie above the diagonal that corresponds to barcodes of the zero length. This graph is called a persistent diagram.

It is convenient to give some simple structure at the neighborhood of the maximum - so-called simplicial structure. Without giving any formal basis we only describe an algorithm that was used. The incremental algorithm for computing homology which we used in our work is described in Edelsbrunner [6]. Modification for two-dimensional matrices could be found in Makarenko et al. [7]. It consists of two sequential steps: filter construction of simplices (for two-dimensional images the simplex is a vertex, an edge or a triangle) and computing the Betti numbers on the created filtration. Let $f(\mathbf{x})$ is a value at pixel $\mathbf{x}$. For the filter construction we need to determine the function value for each of simplices. In order to do this we associate each pixel $\mathbf{x}$ of the image with the vertex. We define the value for the remaining simplices by assigning the maximum of values between their vertices. After that we iterate through all elements of the ordered sequence and add each of them to the filter. At the same time, attaching the new vertex to the filter we add all edges and all triangles that can be generated by vertices, which we already have in the filter, and the new vertex. Now Betti numbers could be computed by processing the simplices in the filter and keeping track of changes in connectivity of the obtaining set. If vertices of the current edge belong to different connected components, then after merging them into a single component we suppose that the component, which appeared later than another, disappears "dies". In that way we can keep track of "birth" and "death" of connected components at the intensity levels. To compute the lifetime of holes, i.e. for the number $\beta_1$, we use the same algorithm applying it to a dual graph Makarenko et al. [7]. If we sum all life length for $\beta_0$ and for $\beta_1$ and take difference of them we receive the Euler characteristic of persistence diagram, it was introduced in the PhD of Bobrowski [8].

### 3. Results

We used a time sequence of magnetograms of the full solar disk, obtained with the help of the HMI tool. A time interval between magnetograms was 720 seconds, and the noise level does not exceed 6 gauss. A fragment of 600x600 pixels containing the AR was cut from each magnetogram. For the specified 720 seconds time gap about 800 consecutive images of the same active region passing across the solar disk were available. We used **FI** index of flare productivity to compare the variations to flare activity. Roughly speaking, it measures a weighted amount of energy produced by solar flares of various classes in the finite time interval. The flare classes **FI** were converted to numeric values. The magnitudes of C class flares were not altered, for M class flares the magnitudes were multiplied by 10, for class X were multiplied by 100, and for B class were divided by 10. We present here the results of numerical experiments for two flare-active regions AR 11520 and AR 11158.

**AR 11158** appeared near the center of the solar disk as a compact beta-class bipolar group on February 12, 2011. Within a day it reached delta magnetic class and on 12 February produced a flare of class M6.6. A day later M2.2 flare followed, and, finally, on 15 February X2.2 flare occurred. After that activity of this AR actually stopped. At the Fig. 1athe behavior of the persistent homology difference or Euler characteristics (Eq.1) is represented. Here we could note a depression in the graph preceding the phase of flare activity. The depression is the most obvious about a day before the X flare.

**AR 11520.** This active region appeared on the Sun at July 8, 2012. It was immediately assigned to the class of complex large groups of delta-configuration with possible high flare productivity. Initially, the region was a single large penumbra, which contained many small spots of the opposite polarity. In the course of evolution it began quickly disintegrate into several compact regions. Against all expectations, the AR11520 produced only four flares of M class and one flare X1.4 on 12 July. The last flare approximately corresponded to the localization of the group near the center of the solar disk. After that the AR 11520 flare activity stopped. At the Fig. 1b evolution of the Euler characteristic for the AR 11520 obtained by the persistent homology is shown. Again we can see well-marked variations in topological complexity of the field before the X flare.

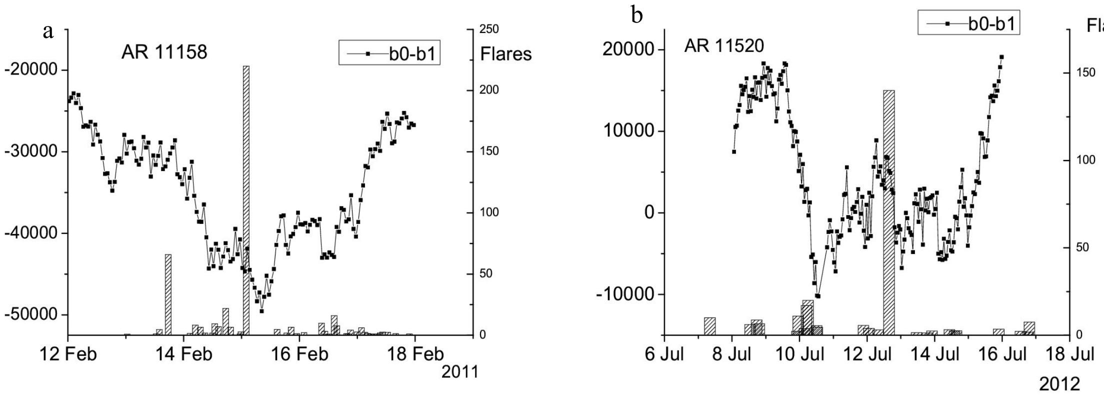


Fig. 1. Dynamics of Euler Characteristics of persistent diagram (b0-b1) for (a) AR 11158 and (b) AR 11520

## 4. Conclusion

The main purpose of the present work was to develop some topological approaches for the analysis of the dynamics of magnetic field of the Sun, which are focused, to the search of pre-flare scenarios. Approach is shown on an example of AR11520 and AR 11158. For these active regions the strongest flares of the class X far from the limb of the disk were observed. Using the corresponding sequence of magnetograms we obtained time variations of the Euler characteristic of persistence diagram. The AR under the study show different dynamics which are tracked by changes in topological characteristics. Typically significant variations of the Euler characteristic of persistence diagram often precede the flares. Note that the results presented in this paper confirm the results from our earlier works obtained from the MDI/SOHO magnetograms, see Makarenko et al. [9] and Knyazeva and Makarenko [10]. This fact slightly compensates for a lack of the adequate statistical sample restrictedby the low level of the solar activity at the present time. Nevertheless, topological approaches satisfy the empirical considerations of the primary role of topological changes in the magnetic fields of active regions.

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